Underground shield tunnel enlargement work

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1. FORWARD

Tunnels located in the big cities of Japan are normally constructed by shield tunnelling methods as many of them are on an alluvial plain, and also because of ever-increasing density of the urban population. Shield tunnelling methods, first introduced in the late sixties for the construction of sewerage tunnels and later widely applied to other types of tunnels, such as power-telecommunication cable tunnels as well as subways, is now called "the method for urban tunnelling work." This experience helped us develop the Earth Pressure Balance Shield Method and the Multi-Face Shield Method.

Using the Enlargement Shield Tunnelling Method, we can enlarge the diameter of an existing underground tunnel. With conventional shield methods, the diameter of the tunnel stays the same from one end to the other. However, there are cases in which the diameter needs to be enlarged between the starting shaft and the arrival shaft. In a case like this, before the introduction of the Enlargement Shield Method, we had to make another shaft by the cut and cover method or apply the New Austrian Tunnelling Method after doing large-scale ground improvement work. However, as projects involving tunnelling work in soft ground having high pore water pressure increased in number, the method started to show its weakness in terms of safety, economy and working environment. This led to the development of a method for partial enlargement of the diameter of an existing shield tunnel.

This report is on tunnelling work in which we enlarged a tunnel with a diameter of 6.6 metres constructed in a diluvial deposit with high pore water pressure, to one of 9.2 metres in diameter for a length of 30 metres directly under a street with heavy traffic.

2. THE OUTLINE OF THE METHOD

In this particular method, an enlarged space is constructed by excavating around the primary shield tunnel (the existing tunnel) with a shield machine in the direction of the tunnel's axis in the shape of a ring, replacing the segments built at the time the primary shield tunnel was driven with the new segments having the desired outer diameter. The Circumferential Shield, which is segmented, is brought through the primary lining in sections and assembled at the Circumferential Shield starting base. This starting base is constructed before commencement of construction of the Circumferential Shield. Figure 1 shows the work procedure.

This particular method is patented in the U.K., the U.S.A. and Japan.

3. THE OUTLINE OF WORK

The tunnel we worked on was the Minamisenju cable and utility shield tunnel right under Route 4, an ongoing project of the Ministry of Construction. The part of the tunnel where it crosses Loop 5 had to be enlarged because that was where the power and telecommunication cables had to branch into other directions. Since the traffic around that particular intersection was among the heaviest in Tokyo, the Enlargement Shield Tunnelling Method was applied.

The area around the site is low, only three metres above sea level where alluvial and diluvial deposits lie. At a depth of 40 metres where the work was done is diluvial deposit, and right above the tunnel is a layer of sand and gravel. At the depth of the excavation and below is a layer of sand. N value of these two kinds of layers was 50 or larger, and coefficient of permeability was 1.4 $\times$ 10^{-2} cm/s. The pore water pressure measured 2.3 kgf/cm^2 in the centre of the tunnel. The content of the cohesive soil to be excavated was 8% to 10%, the uniformity coefficient, 2.2 to 2.6. This showed very poor cohesion, which also meant poor stability of the face. The Enlargement Shield Machine used for excavation was open type, which made some auxiliary work, such as chemical grouting and/or compressed air necessary to stabilize the face (Figure 2).

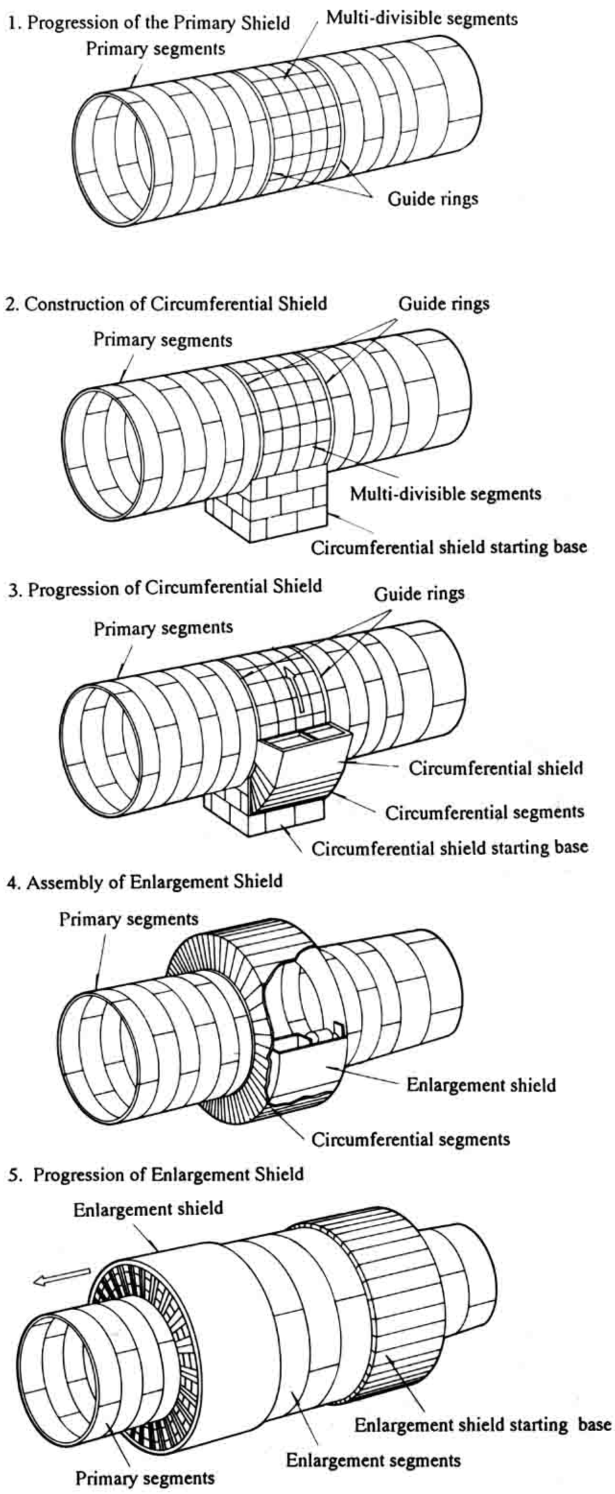

Fig. 1 Order of Execution

4. AUXILIARY METHODS

Since the face is exposed at the time of the construction of the starting base and also while the Circumferential as well as the Enlargement Shields are being built, permeability becomes greater as in-situ stress of ground is released. Therefore, two

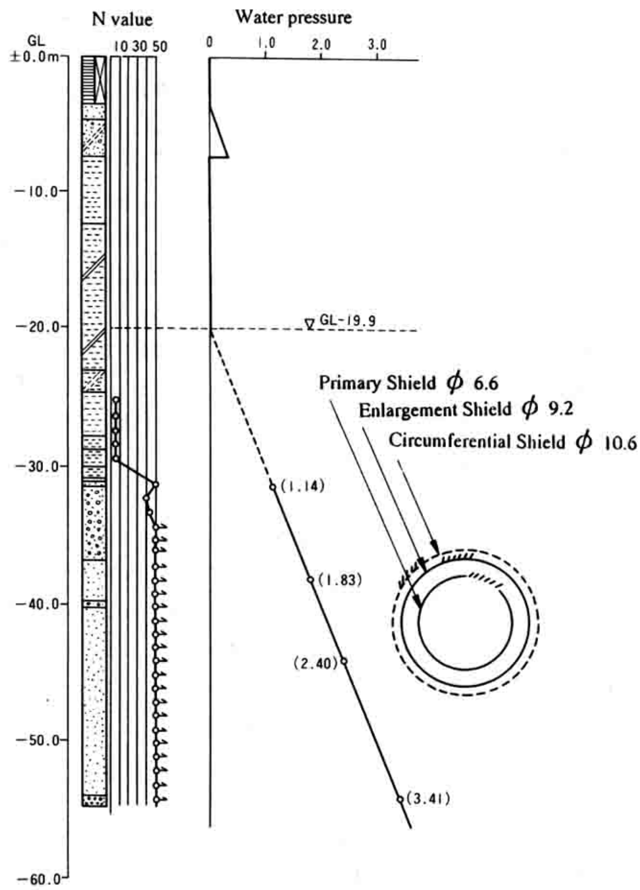

Fig. 2 Strata make-up and Pore Water Pressure Distribution

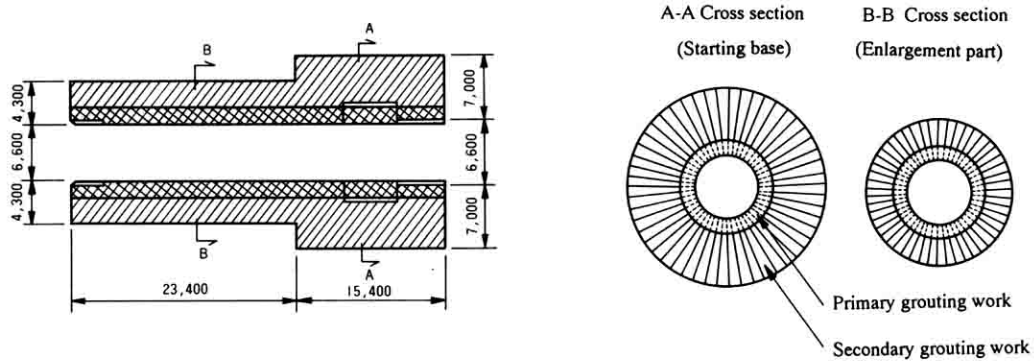

Fig. 3 Area for Chemical Grouting

of the most important factors in the Enlargement Shield Tunnelling Method are ground stabilization and prevention of water inflow into the tunnel. We improved the ground by chemical grouting method and did excavation by the pneumatic method (compressed air).

4 - 1 Chemical grouting method

To construct the starting base for building the Circumferential Shield Machine, we needed to remove some bottom segments of the primary tunnel and excavate a space of 2.2 metres in depth, 3.7 metres in width, and 3.8 metres in length. This makes the primary tunnel structurally unstable with the bottom segments gone. Moreover, release of in-situ stress of the ground under high water pressure would make the face unstable, which might lead to a gush-out of the underground water. Also, at the time of the construction of the Enlargement Shield Tunnelling Method, we were afraid that the ground might be unstable due to release of in-situ stress of the ground. Therefore, we did chemical grouting at a thickness of 7 metres for an outer diameter of 20.6 metres to the ground around the primary tunnel, which was to be excavated by the Circumferential Shield. At the section to be enlarged, we did the same at a thickness of 4.3 metres for an outer diameter of 15.2 metres.

We did the chemical grouting through holes, 50 in all, made around the circumference of the tunnel as well as others made at an interval of 45 cm for the entire length to be enlarged.

Since, in the case of injection from within the tunnel, the pressure of the injection itself works on the segments, we did the grouting in two stages. The first stage of injection was done to improve and stabilize the area for excavation around the segments, an area of 1.5 metres in thickness. The second stage of the injection was done to improve the area around the area improved by the first injection. Also, both the first and second injections had been preceded by cement-bentonite grouting to tighten the soil particles loosened by the excavation of the primary shield (Figure 3).

In order for the grouting material to fill the void between the soil particles, we did the grouting in three steps, 50 cm at each step from within the tunnel toward the ground. In each step, we put a preventer at the mouth of the injection hole to prevent flooding and made injection holes with a hand drill of 19 mm in diameter. The grouting was done from the mouth of the hole after the rod was pulled out of the hole. Since the grouting had to be

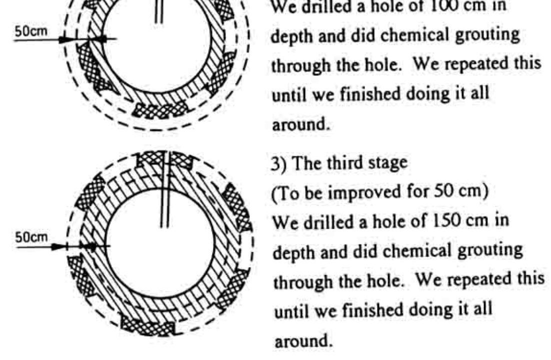

Fig. 4 Primary Grouting Work Procedure

Table I Table of Results of the Secondary Grouting

			Test Values	Values Set for Control
Triaxial Compression Test		C ϕ (qu)	1.8 kgf/cm^2 46.1° 8.9 kgf/cm^2	1.0 kgf/cm^2 45° 5.0 kgf/cm^2
Indoor Permeability Test		k	2.45×10^{-7}~7.50×10^{-7}cm/s	10^{-5}
Permeability Test in the Field		k	1.02×10^{-6}~2.87×10^{-6}cm/s	10^{-5}
Amount of Water Inflow Check	Starting Base Section	k	1.4×10^{-7}~4.5×10^{-5}cm/s	10^{-5}
	Other Sections		3.5×10^{-7}~3.0×10^{-4}cm/s	

done repeatedly at short intervals, and therefore, had to harden quickly under low pressure, we set the gel time between 20 and 60 minutes (Figure 4).

4 - 2 Pneumatic method

Since the pore water pressure during the excavation of Enlargement Shield can well go up to 2.7 kgf/cm^2 and the face would be exposed, it was necessary to prevent the underground water from flowing into the tunnel by pneumatic method as well as by chemical grouting. In order to determine the pneumatic pressure, we dug a hole at the starting base for the Circumferential Shield. The hole was two metres in depth and 350 mm in diameter. We varied the compression pressure from 0.5 to 2.0 kgf/cm^2. We found that when compressed at 1.0 kgf/cm^2, the speed of the water coming up diminished. This led us to decide to set the pressure at 1.2 kgf/cm^2 since the face would be exposed during the construction work. At the time of the actual construction of the base for Circumferential Shield, we set the pressure at 1.5 kgf/cm^2, and at the time of the Circumferential and Enlargement Shield works, at 1.2 kgf/cm^2.

5. CIRCUMFERENTIAL SHIELD WORKS

5 - 1 The strengthening of the primary segments at the starting base

The primary segments are removed at the time of the assembly of the Circumferential Shield Machine, and they are also removed from underneath as the excavation by the machine proceeds, which makes the primary segments structurally unstable due to the lack of their circular shape. In order to stabilize the primary segments structurally, we put supports around the opening made for the construction of the starting base. Though the guide rings are put around the primary segments to lead the Circumferential Shield Machine, these rings have to be temporarily removed while the machine is being assembled. This means that the rings lose their stable circular shape. They resume their circular shape when the assembly of the shield machine has been completed. However, the movement of the shield machine puts the load on the guide rings unevenly. Therefore, we needed to add some support to the primary segments between the guide rings so that they would not give way.

5 - 2 Construction of the Starting Base for the Circumferential Shield

The primary segments at the bottom of the tunnel had to be removed so that we could construct the starting base for the Circumferential Shield Machine.

Prior to the work, we had done chemical grouting to stabilize the ground as well as to prevent water inflow into the tunnel. We also decreased the amount of water inflow by the pneumatic method. When all of this was done, we cut the invert of the primary segments and excavated a square space directly beneath the tunnel. For earth retaining purpose, we used steel cribs. These cribs were placed from the top as the excavation progressed (Figure 5).

Also, together with the chemical grouting and the pneumatic method, we decreased the amount of water inflow into the tunnel by the well-point drainage method. Simultaneously, we checked on water inflow and the solidity of the ground.

We applied some back-fill grouting to the void between the steel cribs and the ground. After the excavation was done to the desired depth, we put the base concrete in at once in order to stabilize the base.

5 - 3 Progression of the Circumferential Shield Machine

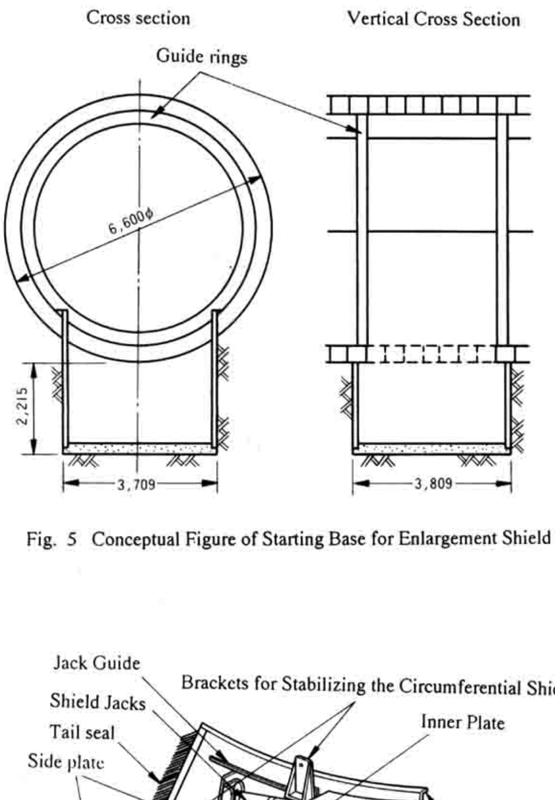

Fig. 5 Conceptual Figure of Starting Base for Enlargement Shield

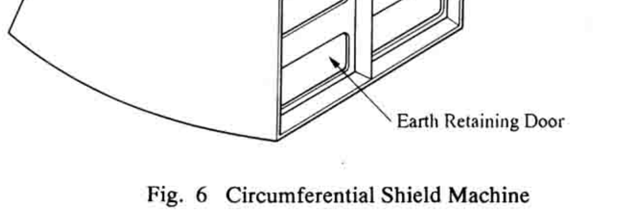

Fig. 6 Circumferential Shield Machine

The Circumferential Shield Machine weighing 18 tf was assembled at the starting base (Figure 6, Photograph 1).

Prior to the Circumferential Shield work, we did bore logging to a depth of 1.5 metres using a rock drill through a valve placed on the slide gate of the face of the Circumferential Shield Machine so that we would be able to check the effects of the chemical grouting during the excavation. Three things that had to be checked on were the volume of water inflow, its sand content, and the stability of the bore wall. We also did some additional grouting where necessary.

The ground had been solidified by chemical grouting so that we could do the excavation manually with picks. We removed the primary segments as we proceeded with the excavation, pushing the shield machine ahead and erecting the segments with a multi-segment-extension erector. We put 50 steel segments, each of which was made up of five pieces, around the primary tunnel (Figure 7).

When this was done, we injected back-fill grout with high plasticity through the injection holes

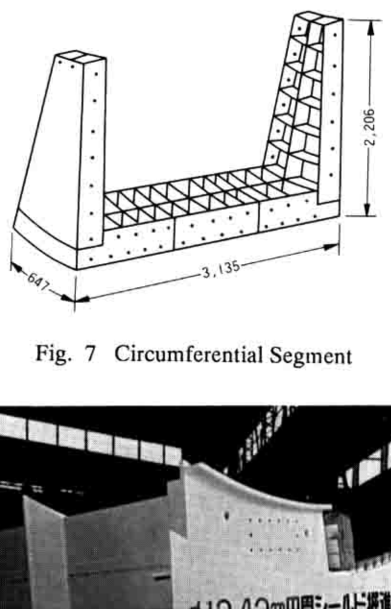

Fig. 7 Circumferential Segment

Photo. 1 Circumferential Shield Machine

made on the Circumferential segments at a pressure of 2.0 kgf/cm^2 or under. When the Circumferential Shield was put around the tunnel, the steel earth retaining cribs were also cut and removed. Then, the Circumferential Shield was pushed forward to the starting base. After all this, the shield jacks were disassembled and put away, but the skin plates were left buried. We put the Circumferential segments within the remaining skin plate so that the segments would acquire the shape of a complete ring.

6. ENLARGEMENT SHIELD WORKS

The Enlargement Shield Machine is an open shield machine with a bi-cylindrical structure connecting the outer skin plates to the inner plates, surrounding the existing segments, with web plates. The whole machine weighs 110 tf. The machine's hood is divided into 12 work sections, and in each of them is a pair of earth retaining jacks. Also, to retain the earth on the upper part of the face, we set up seven movable hood jacks as well as four movable work floors, two on either side of the shield machine (Photograph 2).

We chose two-segment extension jacks to save on the length of the jacks. The Enlargement Shield Machine was disassembled into six parts so that it could be brought into the tunnel, and it was reassembled at the base.

Before we started the shield machine, we did a test boring, as we had done at the time of the Circumferential Shield work, with the air auger to check on the stability of the bore wall, the volume of water inflow into the tunnel, and its sand content. We did some additional grouting where necessary. Using the side pieces of the Circumferential segments in back of the machine as a back anchor, we moved the Enlargement Shield Machine forward, pulling out the side pieces, which lay in the path of the machine.

The excavation work was done section by section, and when that was done, earth-retaining work was done using face jacks, lagging, rectangular timbers and so forth. A movable hood was also put on the ceiling of the shield to prevent the soil from collapsing.

Also, to prevent water inflow, we took such measures as chemical grouting method and the pneumatic method. However, water inflow into the tunnel could not be completely prevented, which led us to resort also to pneumatic drainage. This is a

Photo. 2 Enlargement Shield Machine

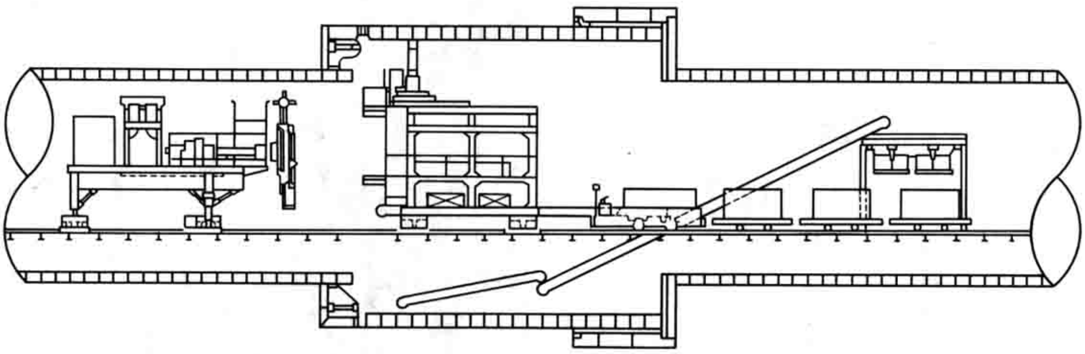

Fig. 8 Conceptual Drawing of Enlargement Shield Work

method for the prevention of water inflow from the face by using pressurized air. In this particular method we drained the water through the 25 holes initially made at every fifth ring of primary segments, or every 2.25 metres, for the purpose of injecting grouting material through injection tubes. The tubes were, of course, removed in advance.

When the excavation was finished, the shield machine was moved forward and the segments were put in place, and the existing primary segments were removed with a multi-segment-extension erector (Figure 8).

The back-fill grouting was done simultaneously with the progression of the shield, and the material used for grouting was of a highly plastic nature.

To waterproof the joints of the segments we put the hydro-expansive sealing material in two layers. We also put cover sealing on the K segment to prevent damage to the sealing material. To waterproof the bolt holes we used bolt packing, the material of which would expand on contact with water.

To save on space for the starting base for the Enlargement Shield Machine, we set the width of the segments basically at 45 cm. These segments were made of steel. Their outer diameter was 9200 mm, and these were divided into 11 pieces. Each ring weighed 6.6 tf.

When a fixed amount of excavation was done, we removed the face jacks, and on finishing the earth retaining work, we immediately applied back-fill grouting to the cutting face. Then, we removed the shield jacks, movable jacks, and placed the segments in the skin plates (Photograph 3).

Photo. 3 Completion of the Enlargement Work

7. CONCLUSION

The Minamisenju cable and utility shield tunnel work was completed in February of 1988, and presently, the other parts of the project are still underway. This particular work confirmed the safety of the Enlargement Shield Tunnelling Method. The method was used later in three other construction projects, and will also be applied in two other projects.